Effect of 3-D magnetic perturbations on pedestal structure and transport in NSTX

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APS-DPP
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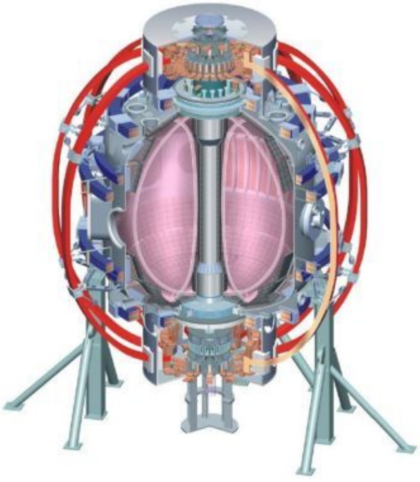
Nov 16, 2011



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Outline

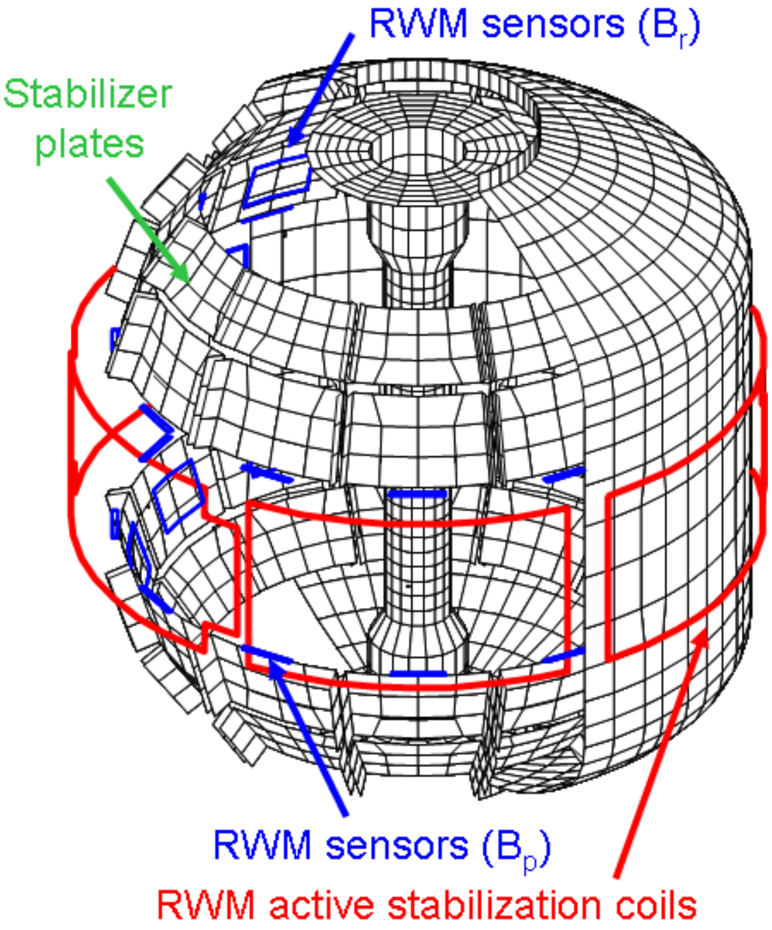
- 3D field application at NSTX
  - n=3 fields applied with midplane coil array
  - Strongest effect is triggering of ELMs during otherwise ELM-free phases

- 3D fields have varying impact on NSTX pedestal profiles
  - Case 1: without lithium, T_e^{ped} increases prior to ELM onset
  - Case 2: with lithium, local flattening of n_e, T_e observed

- Calculations of transport and comparison to experiment
  - Stochastic transport with vacuum perturbation larger than experiment
  - Neoclassical transport due to nonaxisymmetry is small
  - Equilibrium with islands using SIESTA
    - Includes plasma response and enforces MHD equilibrium
    - Island sizes smaller, stochastic transport reduced

Review of ELM triggering: perturbation applied with midplane coil array

- n=3 configuration is used in all experiments presented here

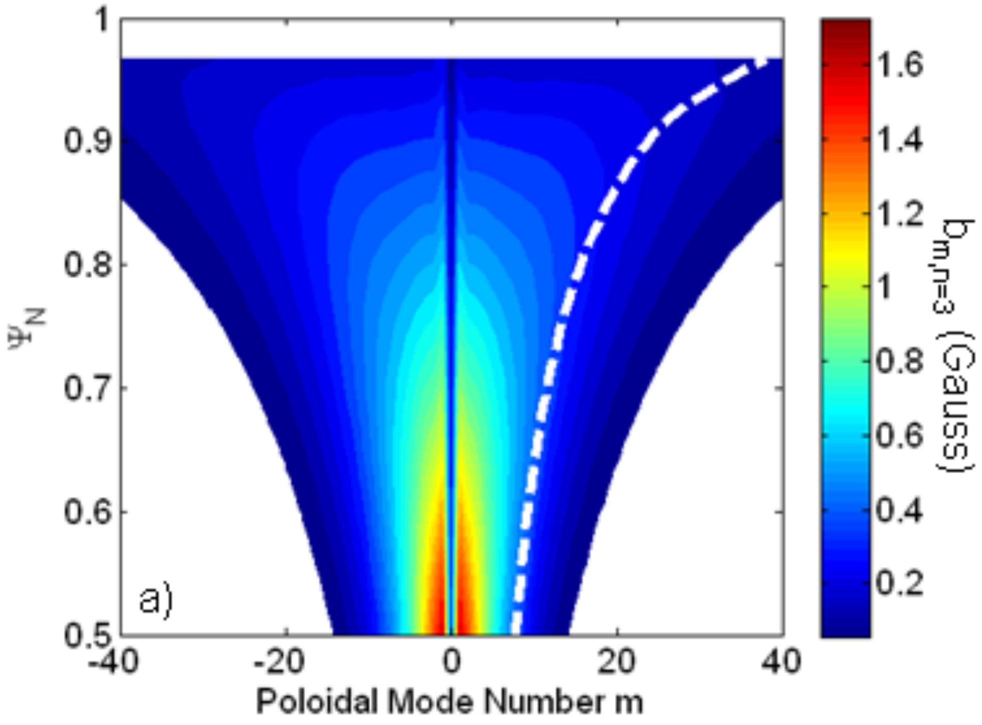


RWM sensors (B_r)

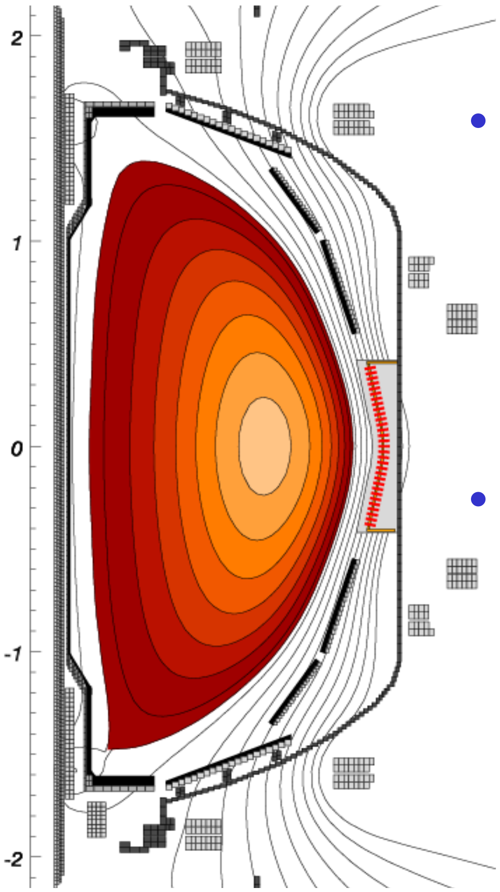
Stabilizer plates

RWM sensors (B_p)

RWM active stabilization coils

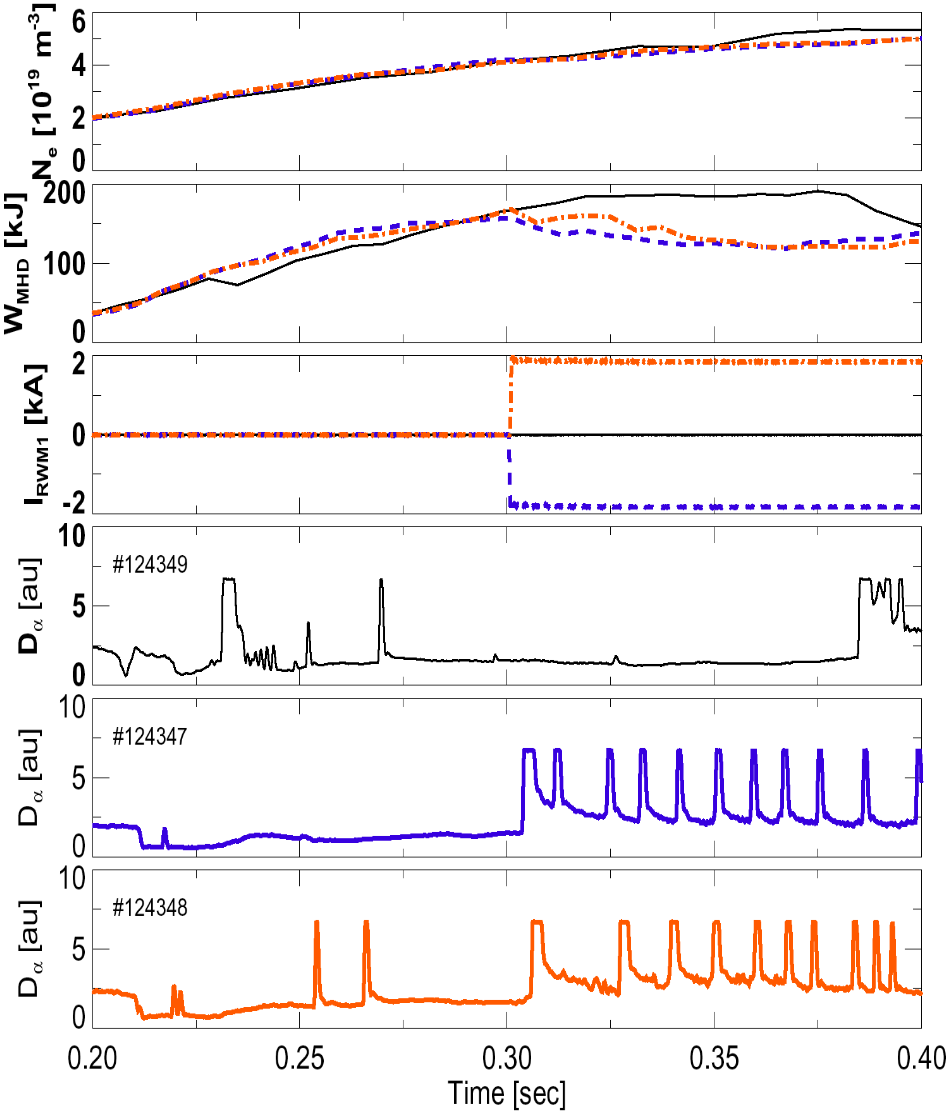


Application of 3D field can destabilize ELMs during otherwise ELM-free phases



- Applied during ELM-free/small-ELM part of discharge

- Parameters of these expts:
  - R/a=85/65 cm
  - B_t=0.45 T, I_p=0.8-1.0 MA, $P_{NBI} \leq$ 6MW



ELM triggering is robust, has been used as a control tool in lithiumized ELM-free H-modes

Typical behavior with Li wall conditioning

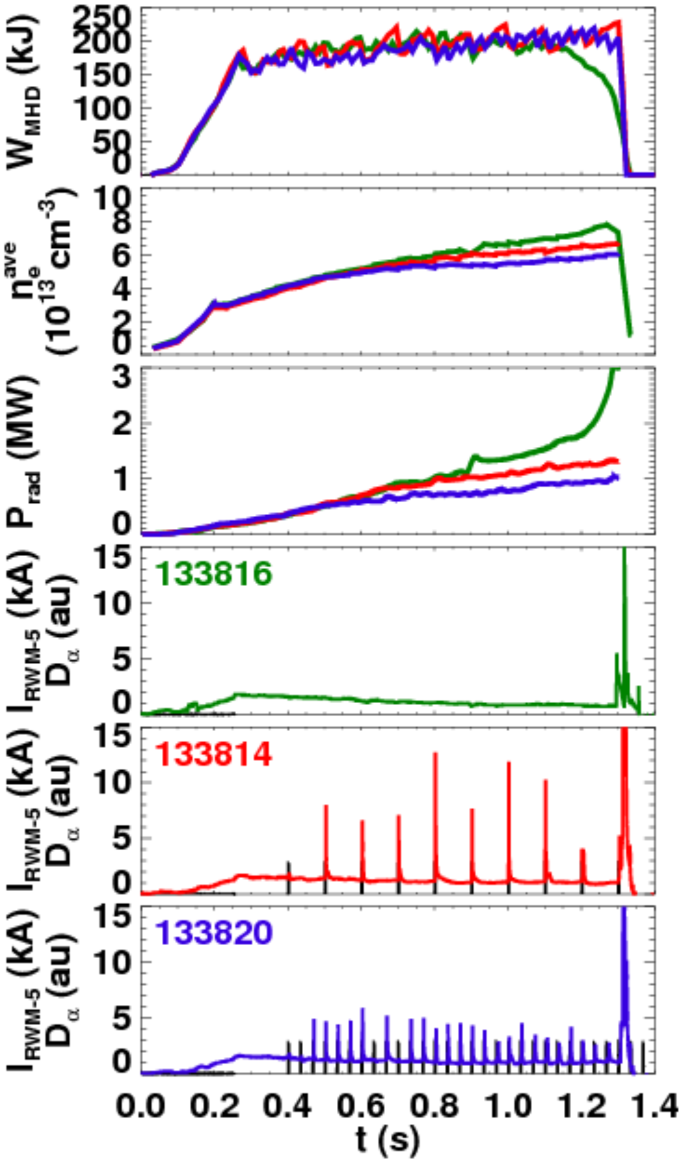
- ELMs completely eliminated
- P_{rad} ramps to ~2 MW; P_{NBI} = 3 MW

Square wave of n=3 fields applied to LITER discharge

- 4 ms pulses, f=10/30 Hz, amp. 2.2 kA

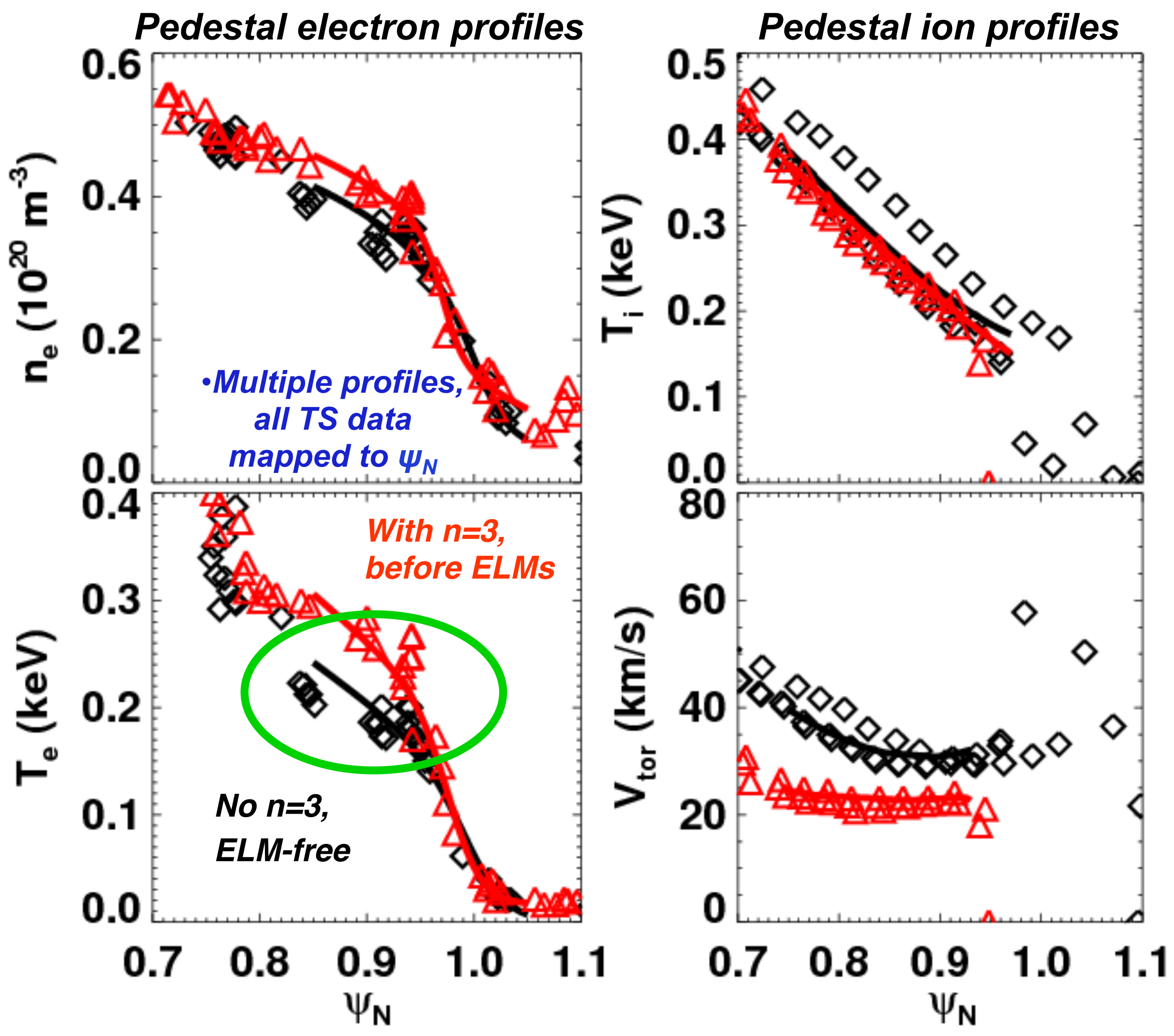
ELMs can be triggered at will

- Full control over ELM timing and frequency
- Used here for discharge control, reducing n_e and P_{rad} ramp rate



Without lithium, T_e^{ped} increases, V_{tor} decreases when n=3 field is applied

- Black profiles: no n=3 applied
- Red profiles: 20 ms after n=3 applied (before ELMs)



•Multiple profiles, all TS data mapped to ψ_N

With n=3, before ELMs

No n=3, ELM-free

- No density pumpout is observed
- T_e, pressure gradient increases after n=3 field is applied
  - Tanh fitting gives ~30% increase in peak pressure gradient
  - PEST shows edge unstable after n=3 application
  - May be related to divertor conditions
- These shots are the focus of this poster

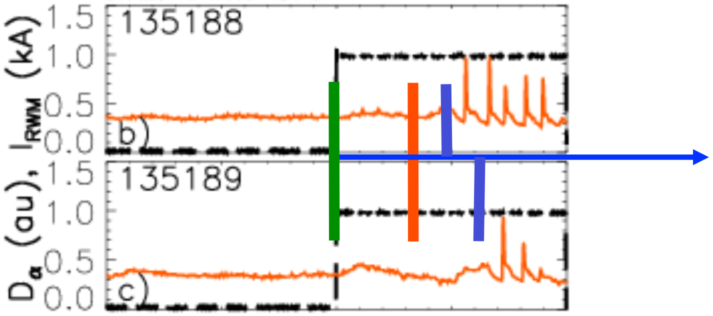
In experiments with lithium coatings, flat spots observed in pedestal profiles with 3D fields

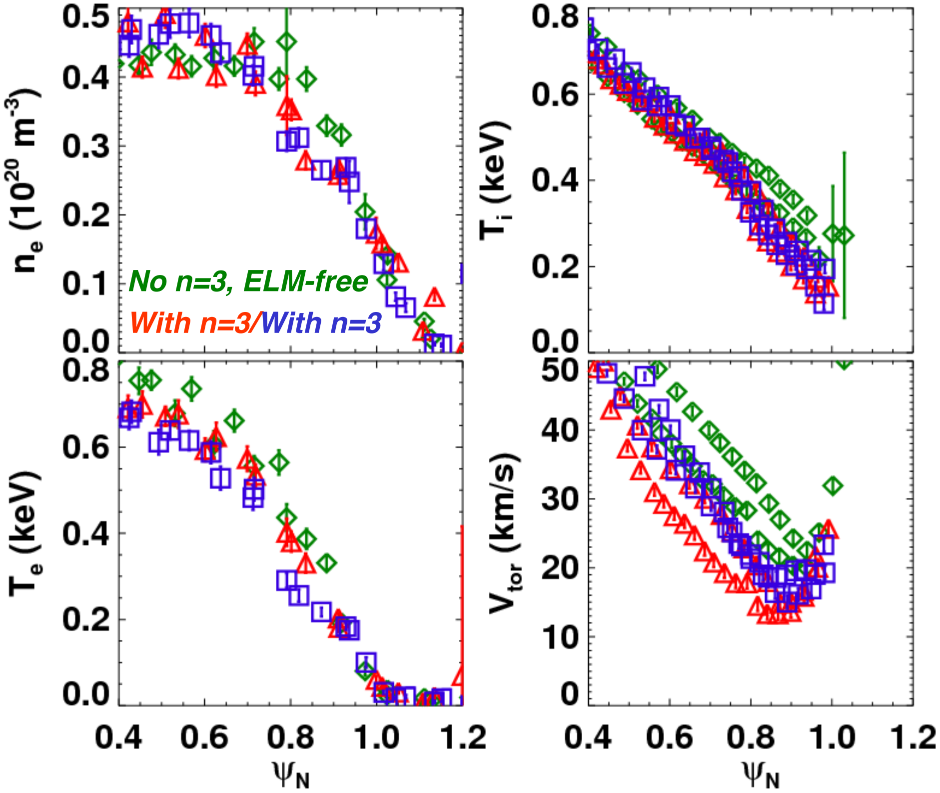
Data combined from several shots, all before ELMs start

Color code: Just before n=3, 30 ms after, ~50/65 ms after

Edge ion temperature, toroidal rotation drop after n=3 field is applied

Te, ne show flattening from ψ_N ~0.8-0.9, similar gradient outside 0.9



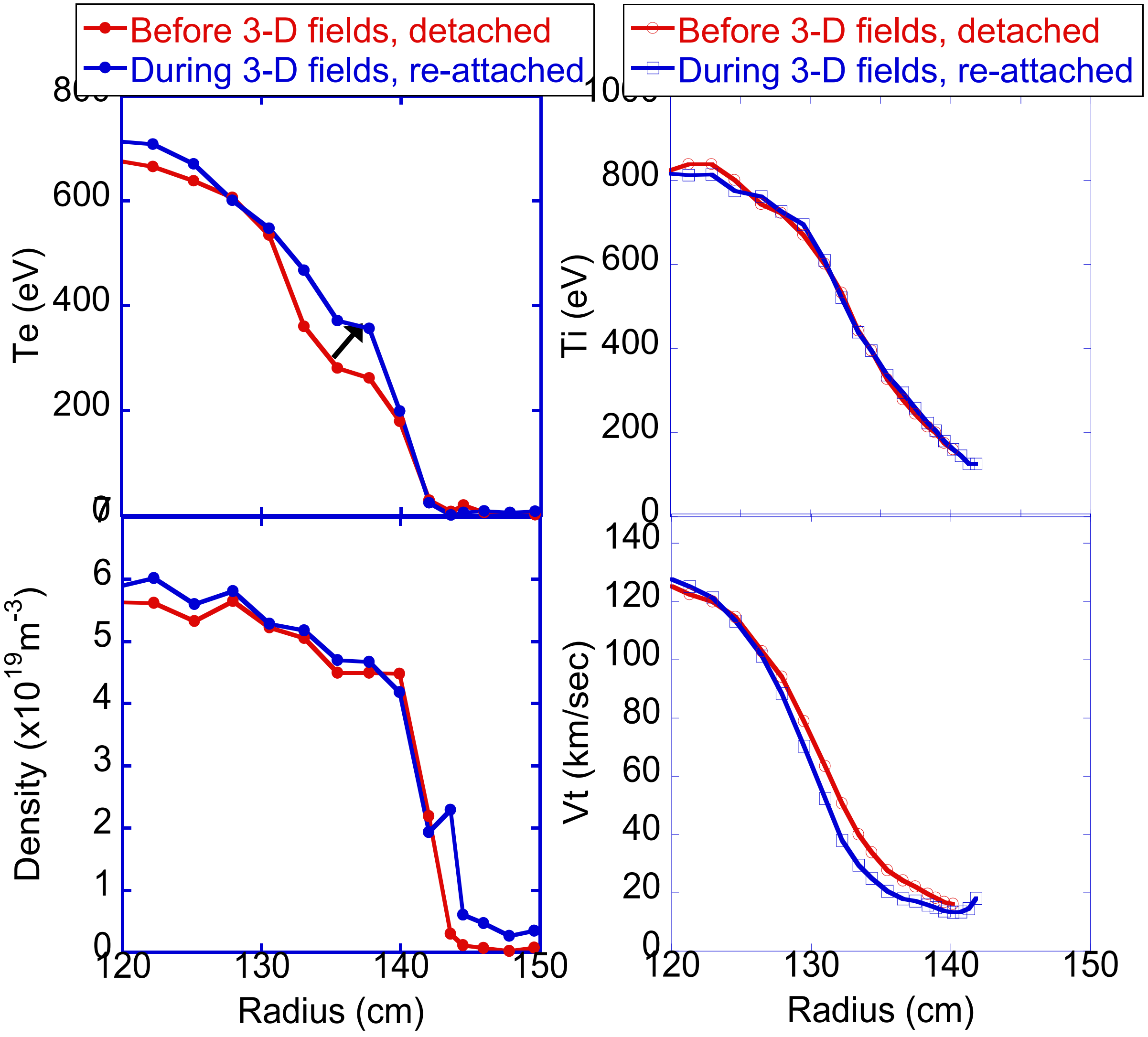


Mechanism for ELM triggering?

Higher resistivity->Type III ELMs?

Increase in T_e^{ped} also observed in experiments studying impact of 3D fields on detachment

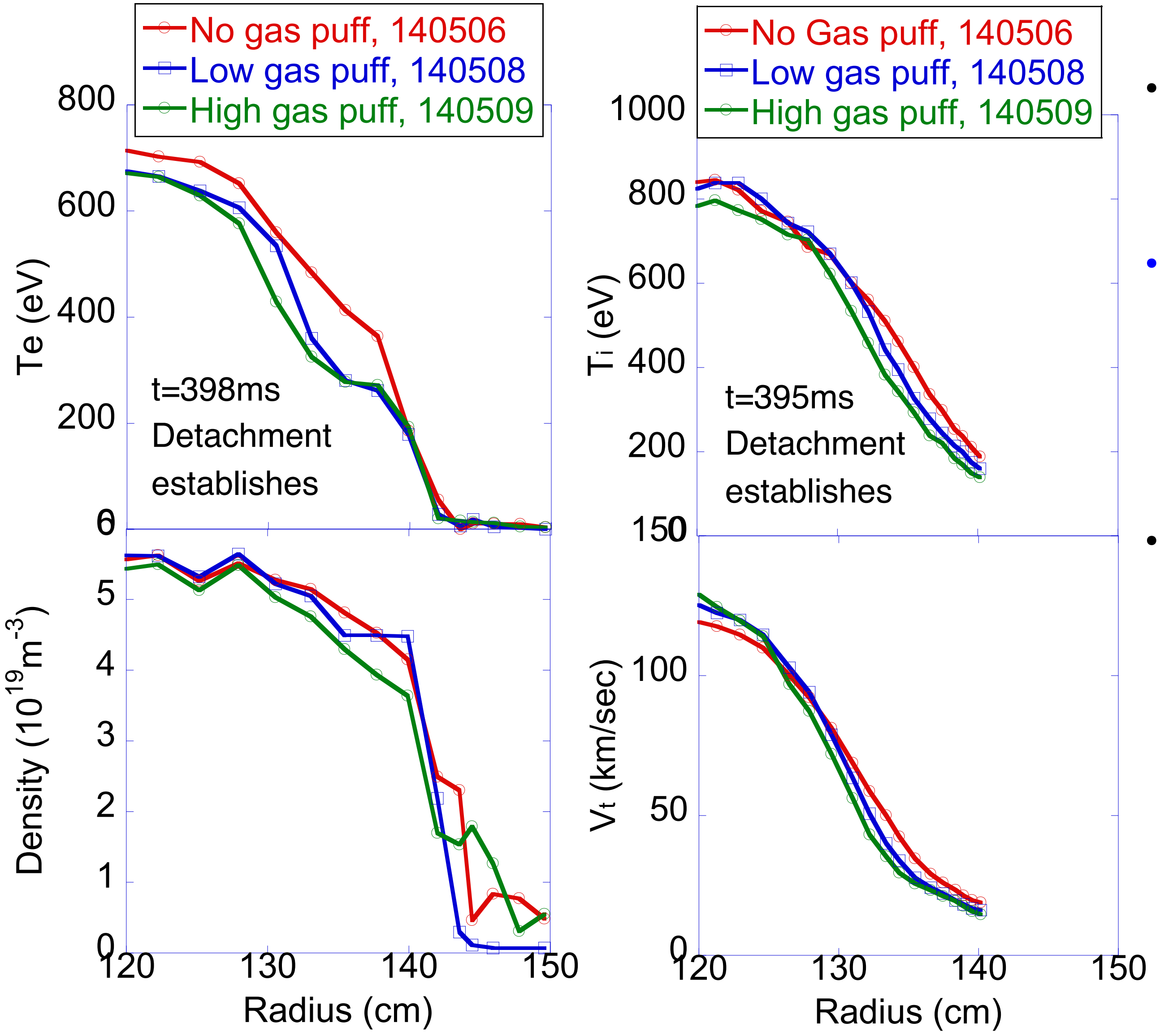
•Low gas puff



- Pedestal T_e profile jumps back up when the re-attachment occurs by 3-D fields application to the low gas puff detachment, while density profile only shows little change
- Ti does not change and Vt keeps decreasing even with the reattachment
- With stronger gas puff, divertor remains detached with 3D fields
  - No T_e increase

J.-W Ahn, N04.04

T_e increase with 3D fields is similar to reduction observed when gas puff induces detachment

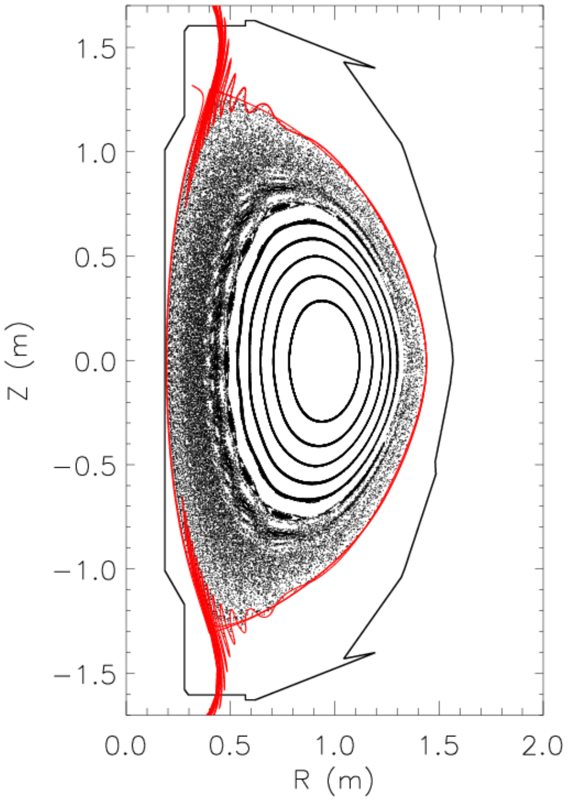


- No 3D fields are applied in these cases
- T_e profile decreases near the pedestal top. Pedestal density also begins to drop
- Suggests that profile change is more strongly linked to divertor characteristics than 3D field induced transport

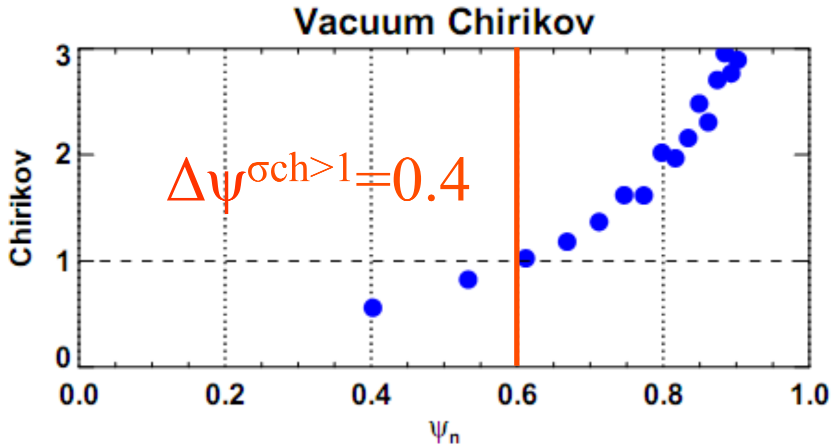
J.-W Ahn, N04.04

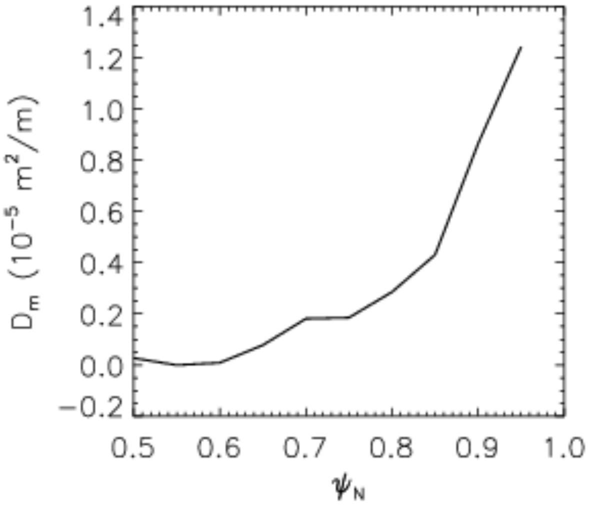
Resonant components are sufficient for edge stochasticity

- Vacuum perturbation yields strong resonance and stochasticity
  - Large edge stochastic region: $\sigma^{ch} > 1$ outside of $\psi_N \sim 0.4$
  - Field line tracing indicates edge magnetic diffusivity of ~1×10^{-5} /m



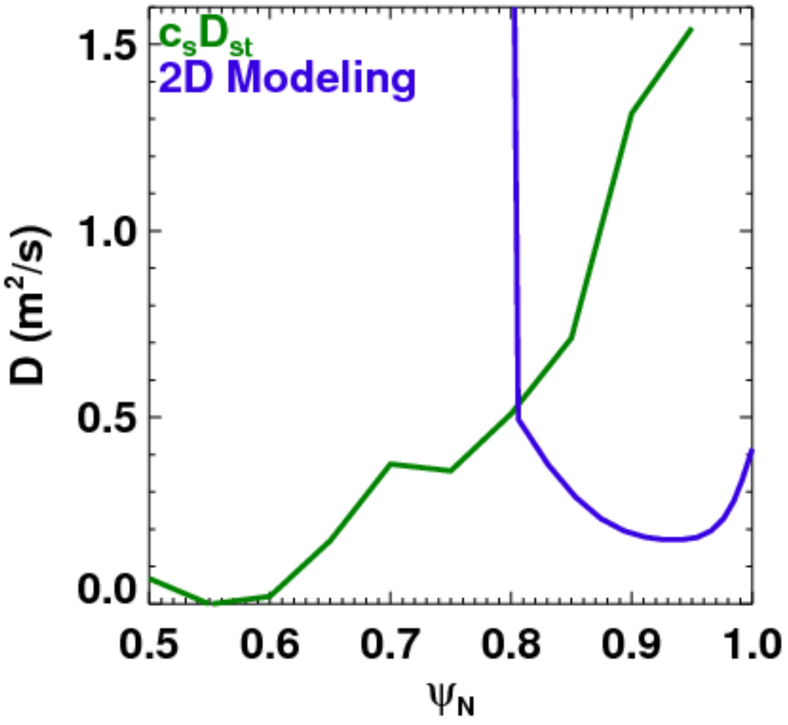
Vacuum fields

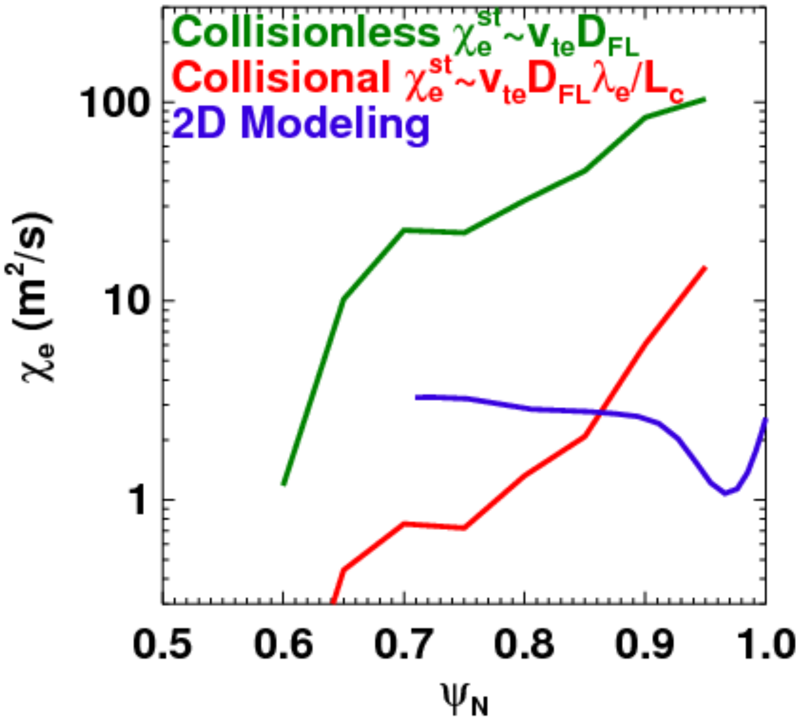




Stochastic transport comparison to experiment

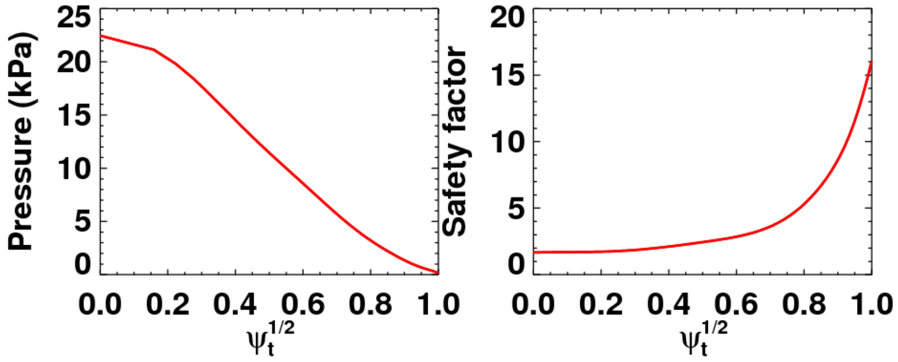
- Experimental diffusivities from 2D interpretive modeling with SOLPS
- Particle transport: comparable to experiment at $\psi_N > 0.8$
  - Should be enough to affect density profile
- Calculated stochastic electron heat transport much larger than experimental
  - True of collisionless across profile, and collisional value at edge
  - Electron temperature profile should be flattened

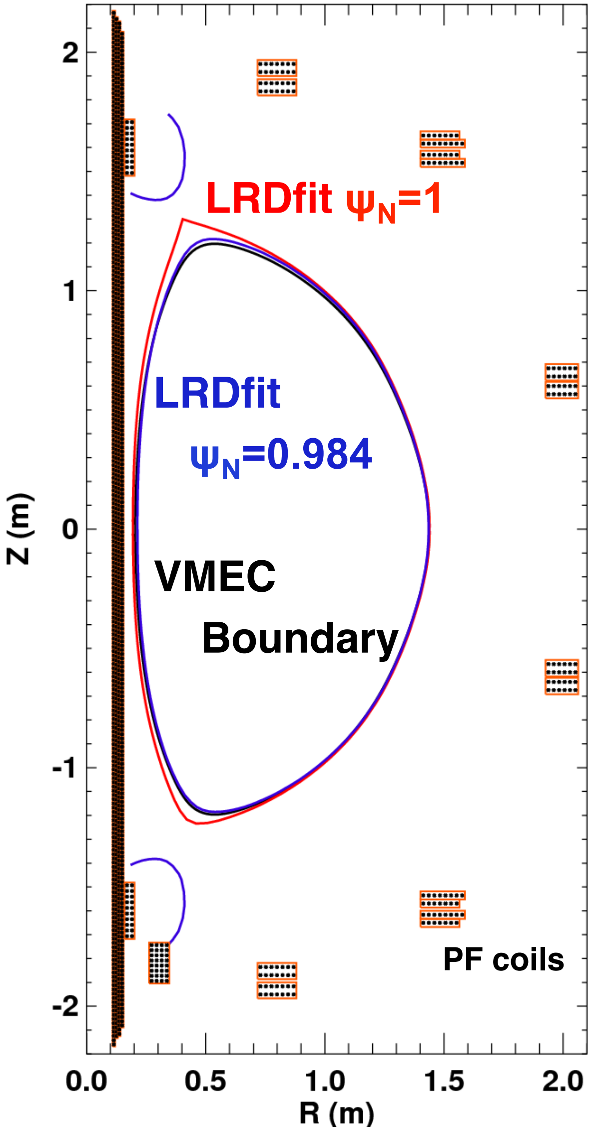




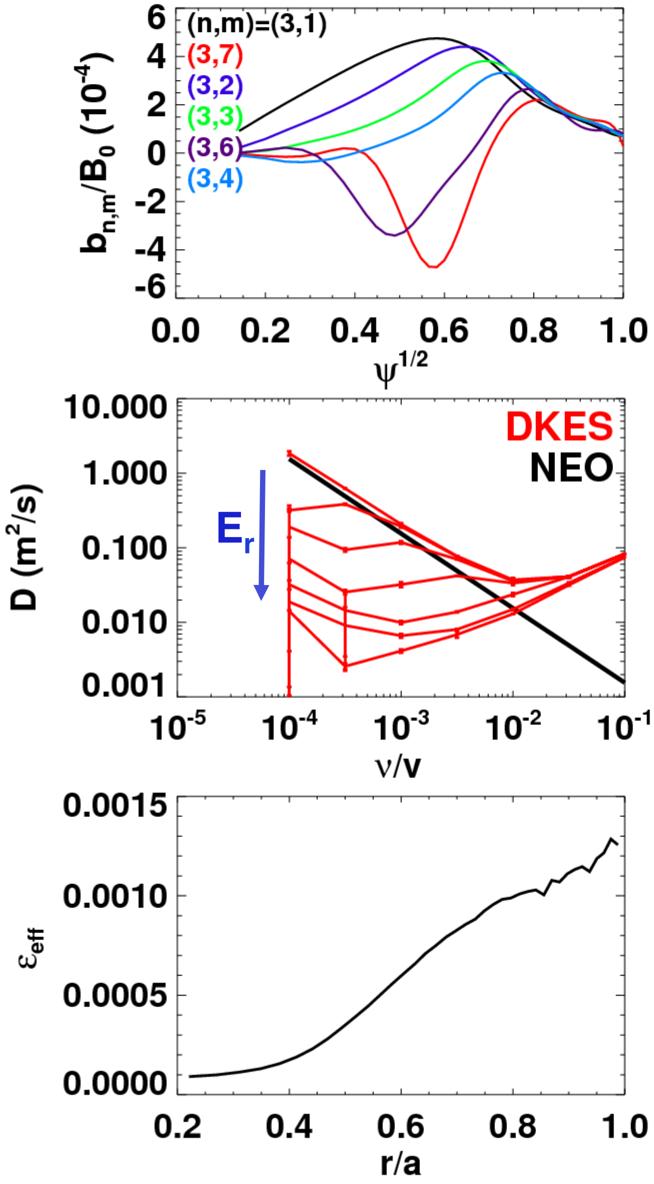
3D equilibrium is generated using VMEC

- 2D equilibrium reconstruction calculated with LRD code
- $p(\psi)$ and $q(\psi)$ from 2D code are input into VMEC
  - Truncated at ψ_N~0.984 to avoid X-point
- Free-boundary VMEC is run using PF/TF coil currents from experiment (but *not* RWM coils)
  - Up-down symmetry is forced in VMEC (2D reconstruction has drsep~5mm)
  - Needed for codes that use VMEC equilibria
- 3D equilibrium generated by adding RWM coils in VMEC run





Nonaxisymmetric terms in the magnetic spectrum lead to increased neoclassical transport



- Breaking of axisymmetry increases neoclassical transport at low collisionality
  - 1/ν regime if radial electric field is weak
  - Stronger E_r gives rise to sqrt(ν), ν regimes

- DKES: Drift Kinetic Equation Solver
  - Van Rij, Hirshman PFB **1** (1989)
  - Full neoclassical transport matrix vs. ν*, E_r

- NEO (effective ripple)
  - Calculates ε_{eff} from field line tracing
  - Yields flux in 1/ν regime (no E_r effects):

$$F_n = -\frac{\sqrt{8}}{9\pi^{3/2}}\frac{v_T^2\rho_L^2}{\nu R^2}\epsilon_{\rm eff}^{3/2}\int_0^\infty\frac{\mathrm{d}z\, e^{-z}z^{5/2}}{A(z)}\frac{n}{f_0}\frac{\partial f_0}{\partial r}$$

  - Nemov, PoP **6** (1999)

Complete treatment of neoclassical transport requires the ambipolar electric field

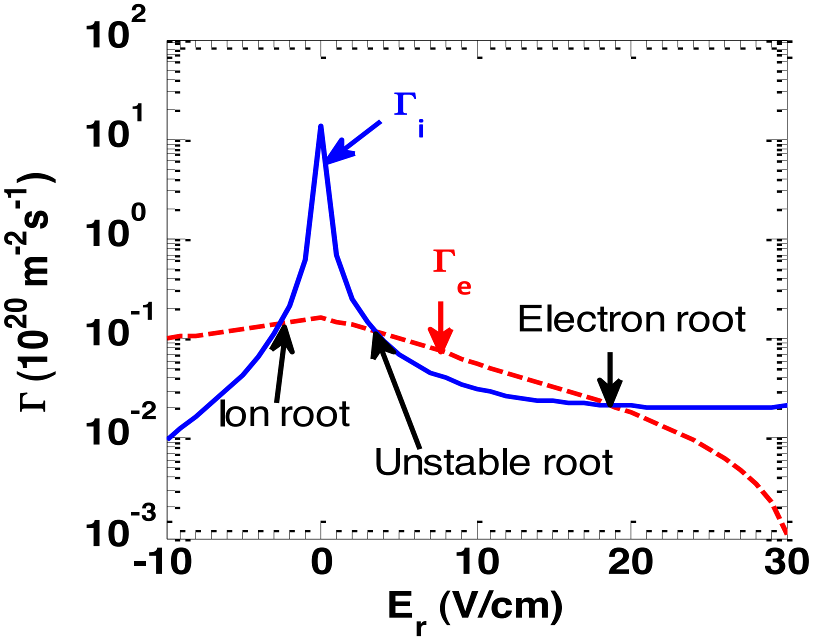
- Fluxes in nonaxisymmetric systems are not intrinsically ambipolar; E_r is determined by enforcing ambipolarity:

$$\sum_s e_s \Gamma_s\left(E_r, D\left(E_r\right)\right) = 0$$

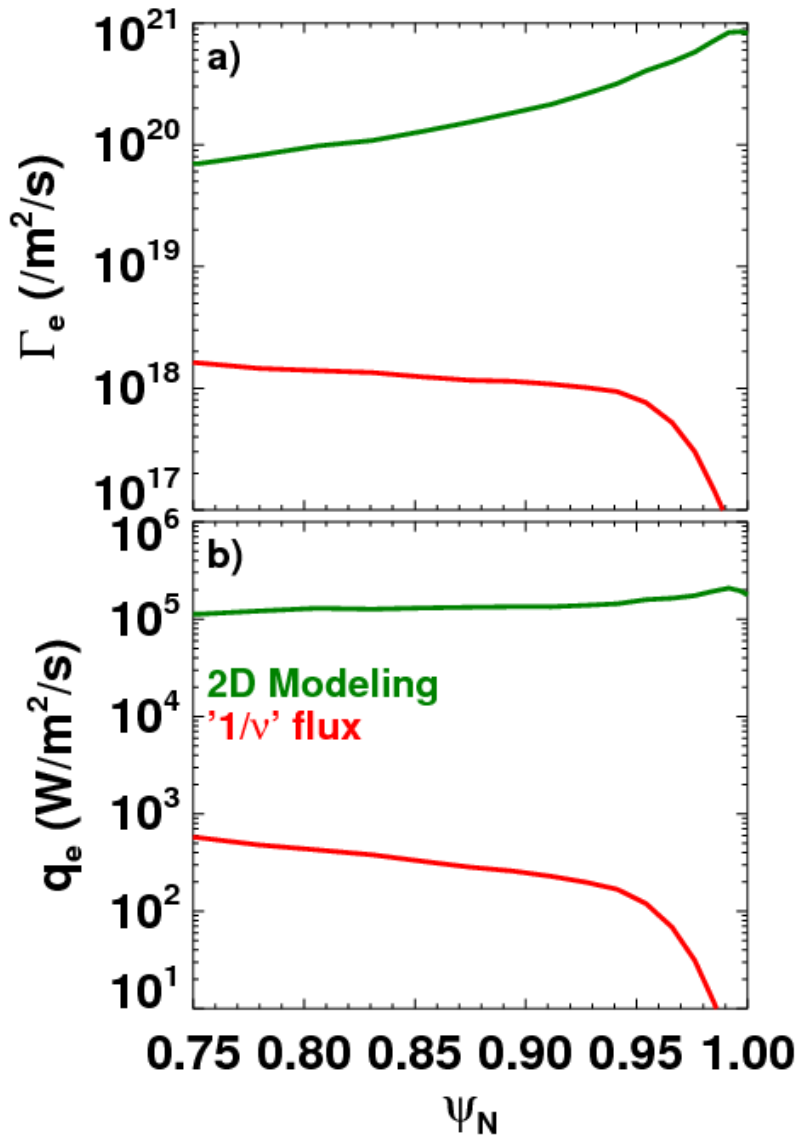
- LMFP with $T_e \approx T_i$ results in three roots
  - **Ion root:** ion flux reduced from E_r=0 level (typical)
  - **Electron root:** (typically only seen with T_e>>T_i and/or strong ripple)

- Calculation of E_r very time consuming (many DKES calculations)

- Instead, consider only 1/ν transport of electrons (i.e., assume E_r~0)
  - Calculated by NEO→much faster
  - Electrons are rate controlling species (E_r brings ion flux down to electron level)
  - Effect of E_r is weak on electrons
  - → Serves as upper bound on particle and electron heat transport



Ripple-induced transport is very small compared to experimental fluxes



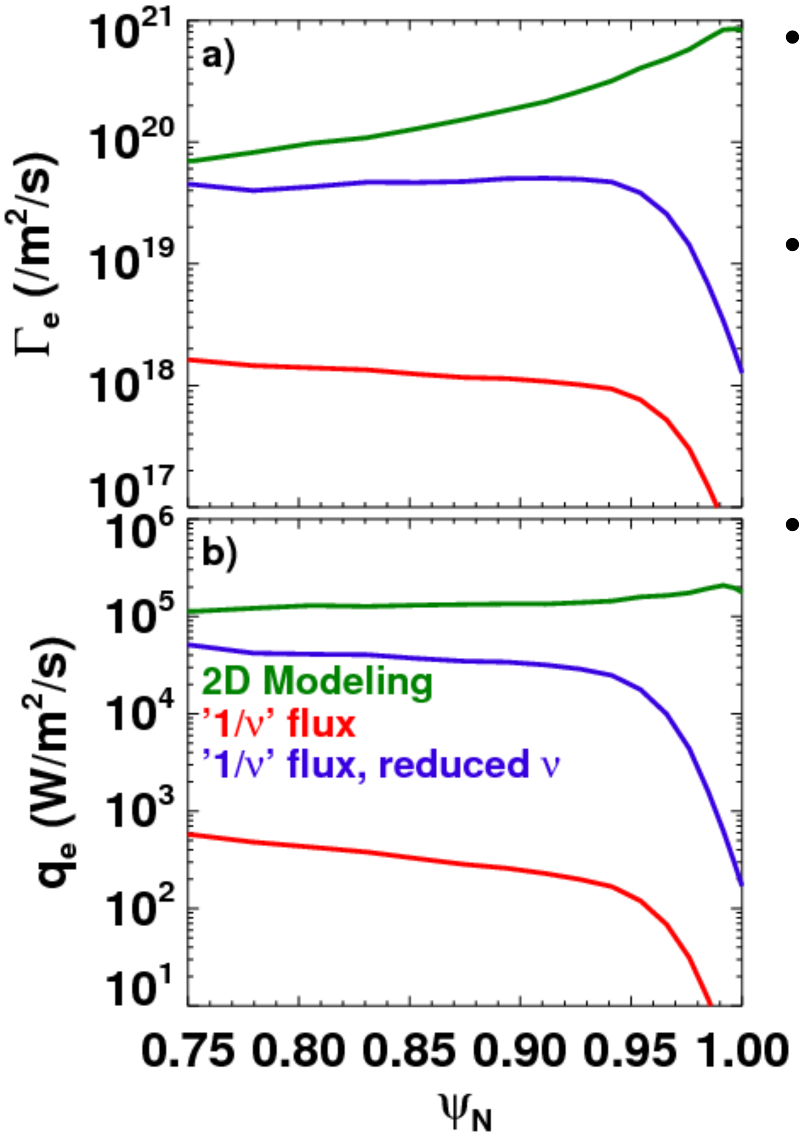
- Electron fluxes calculated for the 1/ν regime
- Both particle and electron heat flux are much less than experiment
  - Consistent with lack of increased transport seen with n=3 field applied
  - Ripple transport alone doesn't appear to play a role
  - Ripple + stochasticity would change ambipolar electric field, may allow larger fluxes

- Ion transport (heat, flow damping) is not considered here, previously shown to be important

  Zhu, PRL 2006

  J.K. Park, PoP 2009

Neoclassical transport might be significant at lower collisionality



- NSTX ELM triggering experiments performed at high collisionality
  - ν^*_{ped}~1-3
- DIII-D shows density pumpout stronger at reduced ν^*
  - Unterberg, J. Nucl. Mat. **386-388** 486
  - Typical ν^*_{ped}~0.1
- With NSTX collisionality artificially reduced, ripple transport becomes significant
  - ν^* reduced by factor of ~20 (n_e/2, Tx3)
  - Neoclassical flux increased to within factor of 3-10 of experiment
  - Experiments at lower ν^*_{ped} might see profile changes due to ripple transport

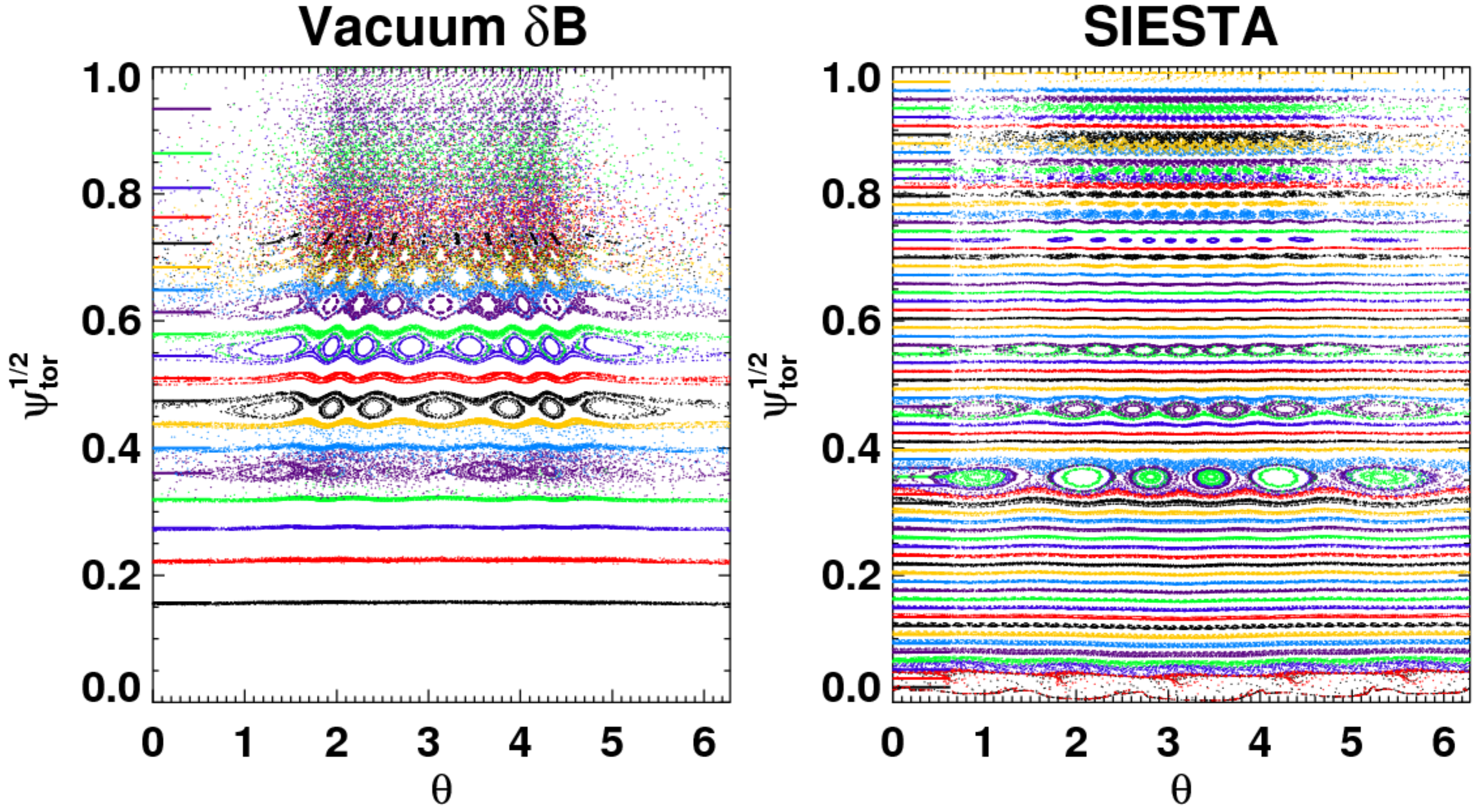
Equilibrium with islands is calculated with SIESTA

- <u>S</u>calable <u>I</u>terative <u>E</u>quilibrium <u>S</u>olver for <u>T</u>oroidal <u>A</u>pplications
  - Under development at ORNL
  - S.P. Hirshman, R. Sanchez, C.R. Cook, submitted to PoP (2011)
- VMEC provides background coordinate system and initial guess at equilibrium
- Drops Clebsch representation of magnetic field, solves for B and p directly
  - Allows $B^s \neq 0$ (s is radial coordinate from VMEC)
  - Islands and stochastic regions can form, if they reduce MHD energy
- Interlaces ideal and resistive iterations
  - Physics based, scalable preconditioner accelerates convergence of ideal steps
  - After each ideal step, resistive diffusion is added to dissipate current sheets at rational surfaces, allow islands to open
- Presently fixed boundary: B·n=0 at VMEC boundary

S.P. Hirshman, GP9.40
C.R. Cook, GP9.41
S. Seal, JP9.125

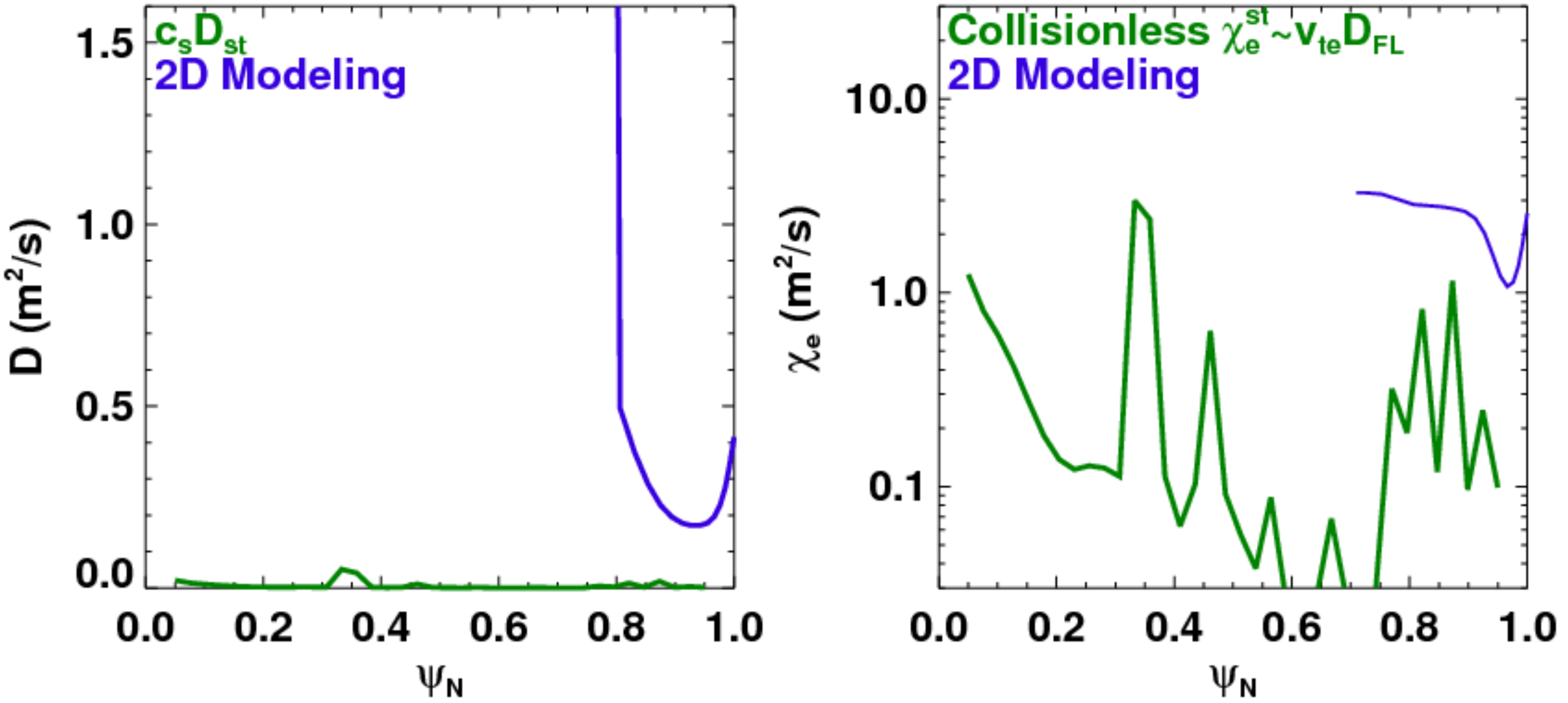
SIESTA solution shows smaller island sizes, less stochasticity than vacuum approximation

- Vacuum RMP gives large stochastic region (consistent with σ^{CH} profile)
- SIESTA equilibrium has islands, but almost no overlap
  - Note that this is fixed boundary, strong constraint on edge



Stochastic transport with SIESTA fields is small compared to experiment

- Field line diffusivity calculated using SIESTA magnetic field
- Stochastic transport is much smaller than experimental rates
  - Consistent with lack of transport increase in experiment



Summary

- The impact of 3D fields on NSTX pedestal transport is relatively weak and inconsistent
  - In some cases, T_e^{ped} increases, may be connected to divertor conditions
  - Other experiments do not show T_e^{ped} increase, but flat spots in n_e, T_e
  - Effect on edge stabilty is more robust: triggering of ELMs

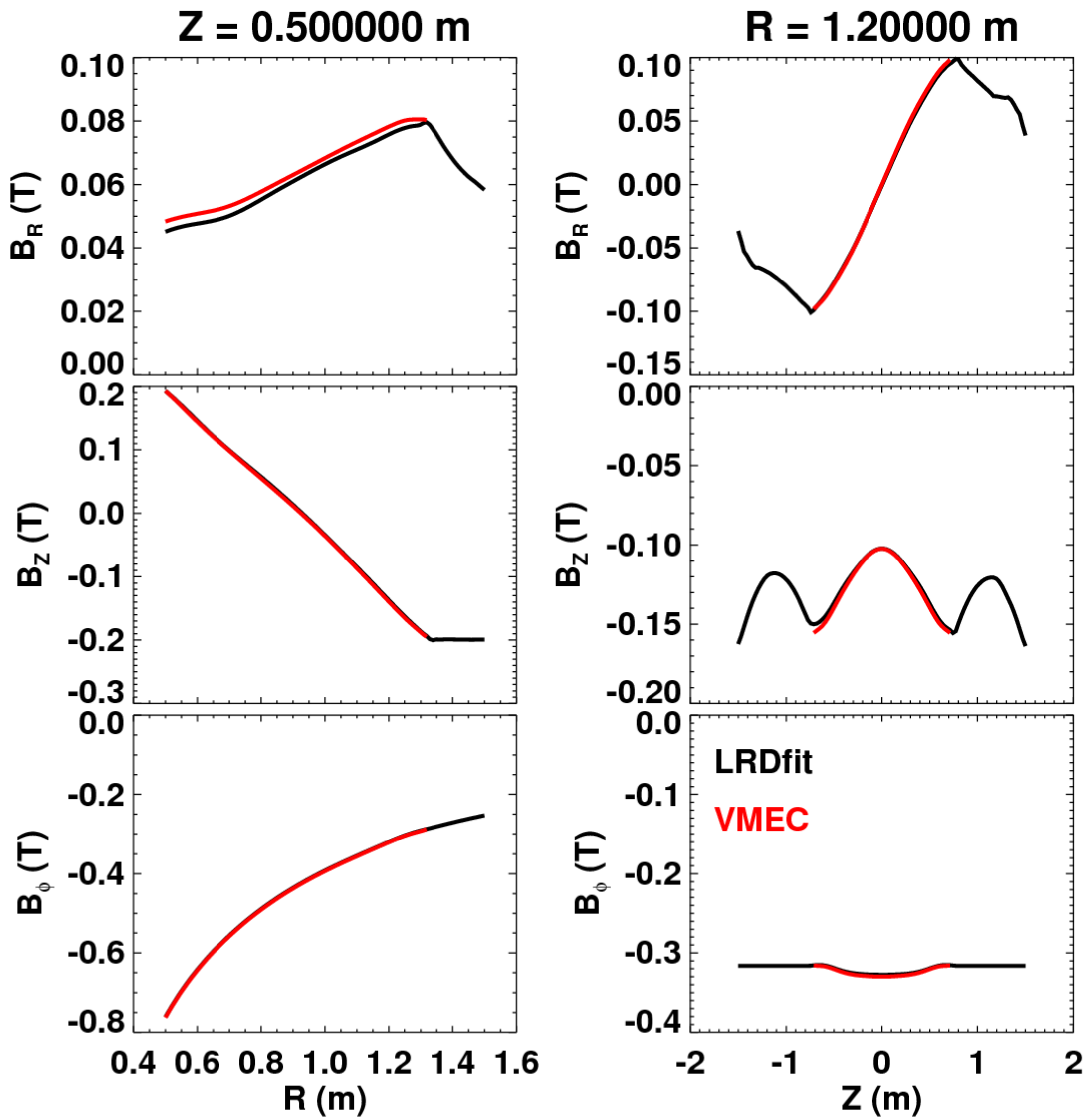
- Calculations show that expected transport change is small
  - Neoclassical transport due to 3D fields is small compared to expeirment
    - May be significant at more ITER-relevant collisionality
  - Stochastic transport is very large if vacuum paradigm is used…
  - But islated equilibrium calculated with SIESTA shows little island overlap, small stochastic transport rates

BACKUP

Calculation of 3D equilibrium with VMEC

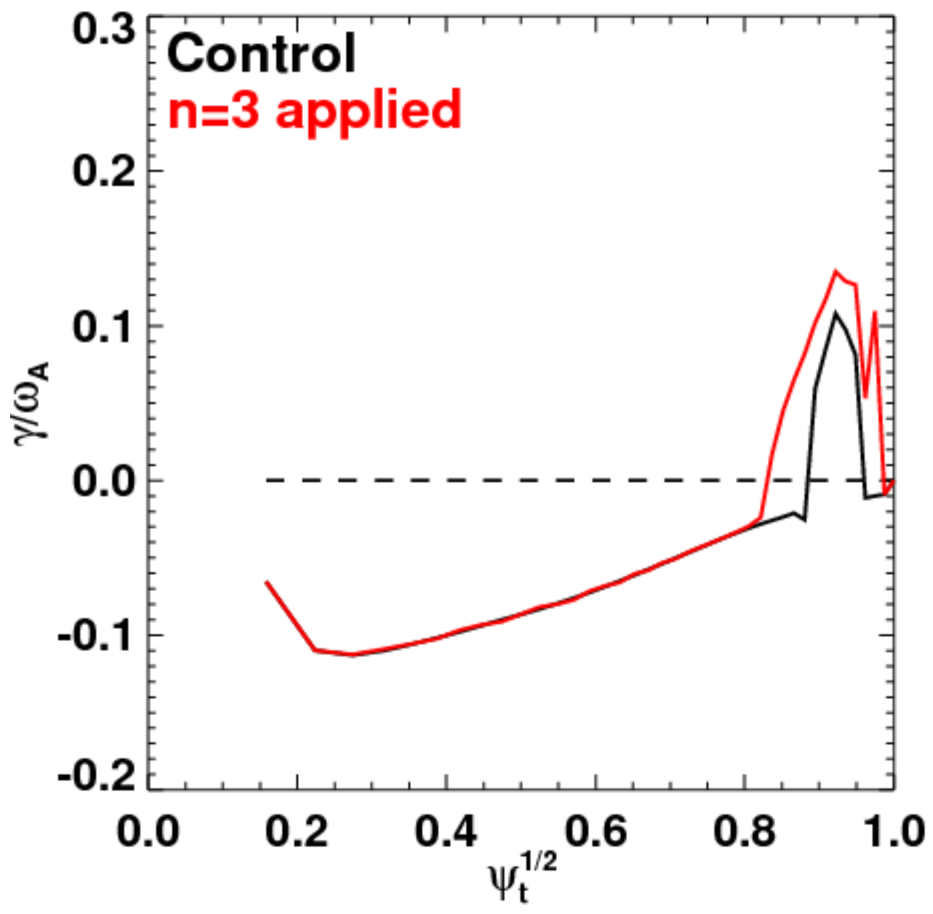
- Variational Moments Equilibrium Code
  - S.P. Hirshman, W.I. van Rij, P. Merkel, Comp. Phys. Comm. **43** (1986) 143
- Minimizes total plasma energy (magnetic + thermal)
  - $W = \int dV \left[\frac{B^2}{2\mu_0} + \frac{p}{\gamma-1}\right]$ -> $F \equiv J \times B - \nabla p = 0$
  - Handles 3D problems with no restrictions on symmetry
- Assumes magnetic field can be written in Clebsch form
  - $B = \nabla s \times (\psi'\theta - \chi'\zeta + \lambda)$
  - Solves for R(s,θ,ζ), Z(s,θ,ζ), λ(s,θ,ζ) that satisfy force balance
  - Requires nested surfaces
- Inputs
  - Radial profiles of pressure, and current or q (vs. toroidal flux)
  - Boundary shape OR coil positions/currents

With 2D equilibrium reproduced in VMEC, RMP fields are added to produce 3D equilibrium



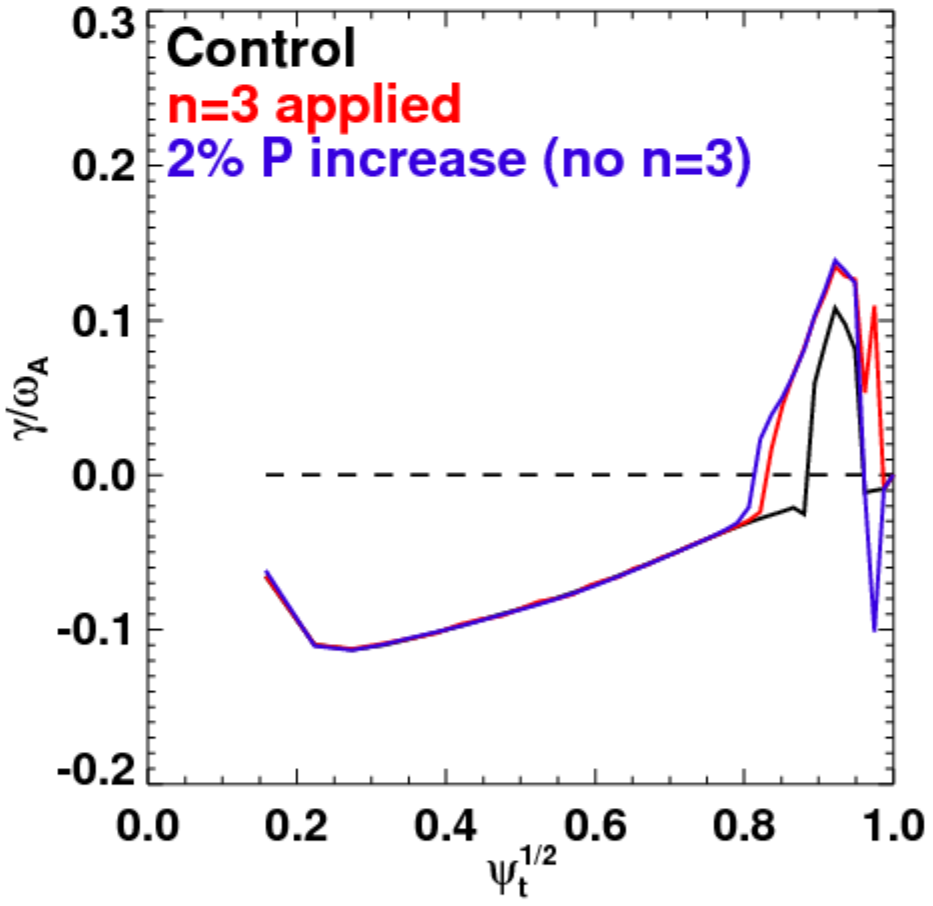
- Magnetic field components from VMEC compared to 2D reconstruction at various points
- Good agreement between found between the two codes
  - Some differences due to up/down symmetry in VMEC
- Finally a 3D equilibrium is generated
  - Re-run VMEC, this time with RWM coils carrying current as in experiment

Ballooning stability is degraded by presence of n=3 fields



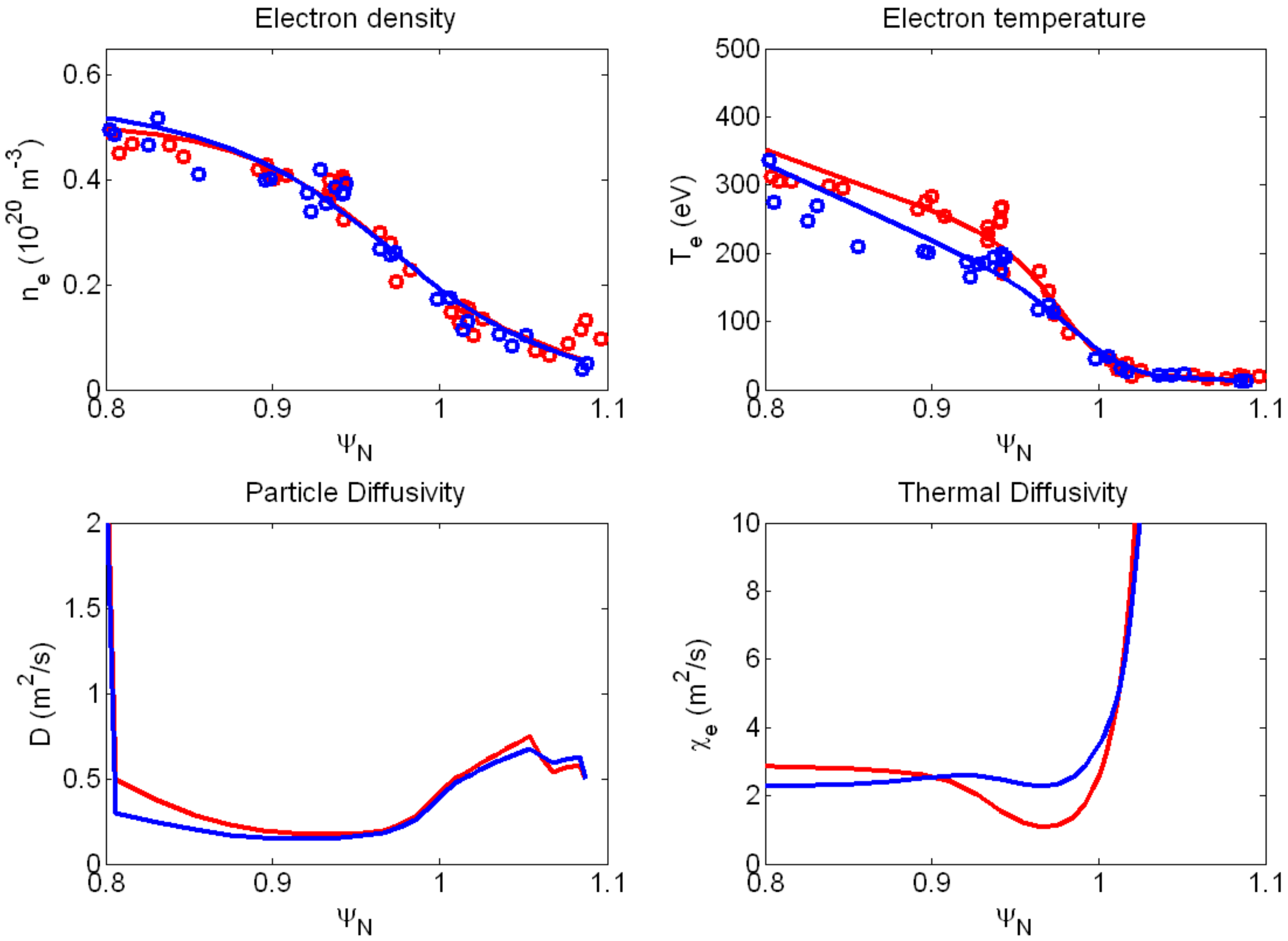
- Infinite-n ballooning stability calculated with COBRA code
  - R. Sanchez et al, Comp. Phys. Comm. **135** (2001) 82
- Control case (no n=3 field applied) shows region of instability near edge
- n=3 field increases instability
  - Region with positive growth rate gets wider
  - Growth rates in unstable region higher
- Suggests at least a trend towards instability with 3D fields applied

Growth rate change can also be realized by increasing pressure by 2% in axisymmetric case



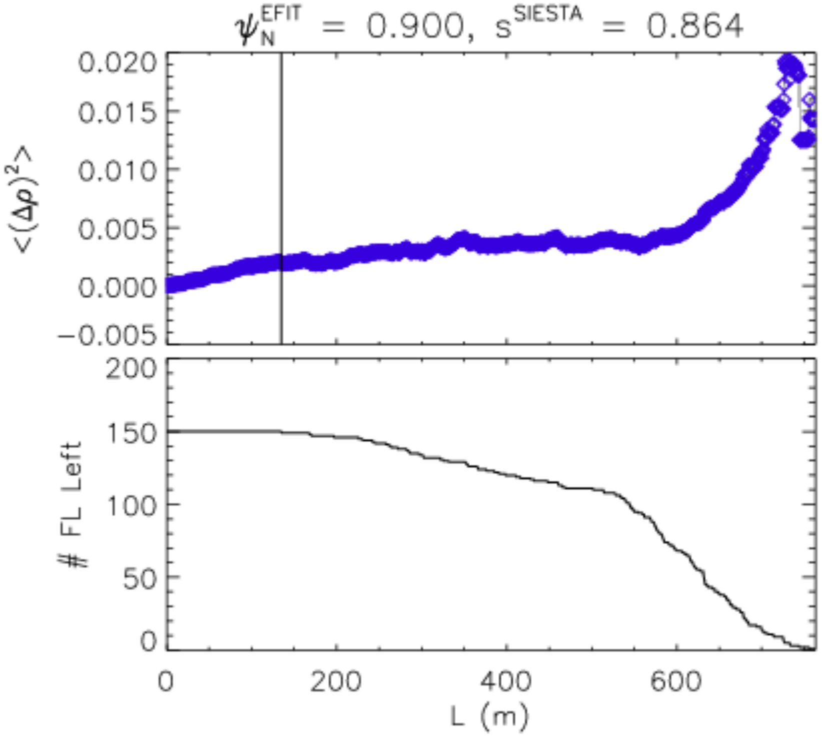
- Axisymmetric case with pressure profile 2% higher examined
- 3D effect only important if plasma is very near stability boundary to begin with
  - ELM triggering seen during robustly ELM-free H-modes
- Low/intermediate-n stability more relevant for ELMs
  - Changes to infinite-n stability may not be reflected in peeling-ballooning stability
  - ELITE/PEST show NSTX ELMs typically n~1-5
  - Low-n stability is being explored with the TERPSICHORE code (W.A. Copper, Lausanne)

Interpretive modeling with SOLPS gives D~0.2, χ~1-2 m^2/s in H-mode transport barrier

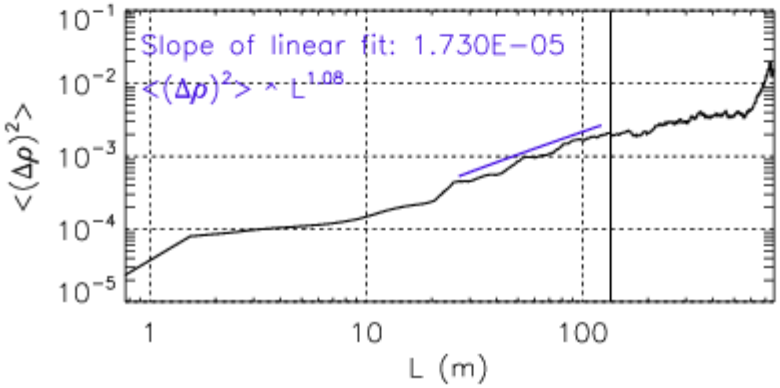


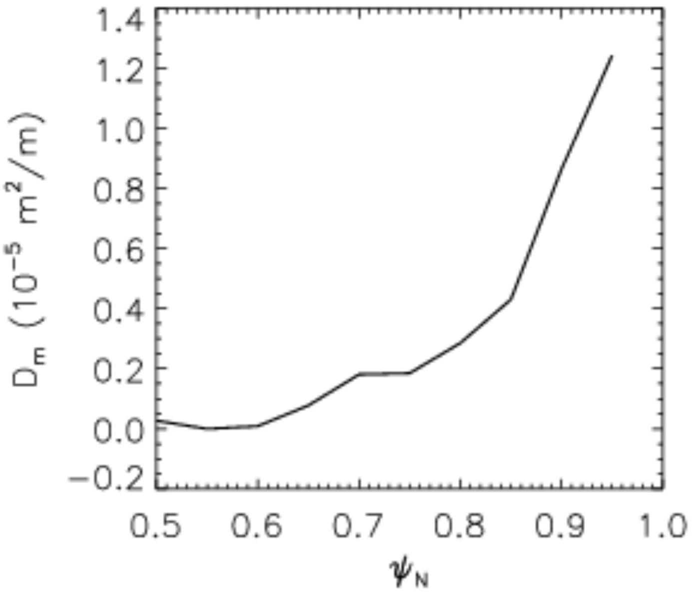
- 2D fluid plasma/MC neutrals code, includes particle fuelling from recycling
- Power, gas puff taken from experiment
- Transport coefficients adjusted to fit measured profiles

Field line tracing used to estimate heat transport in stochastic field



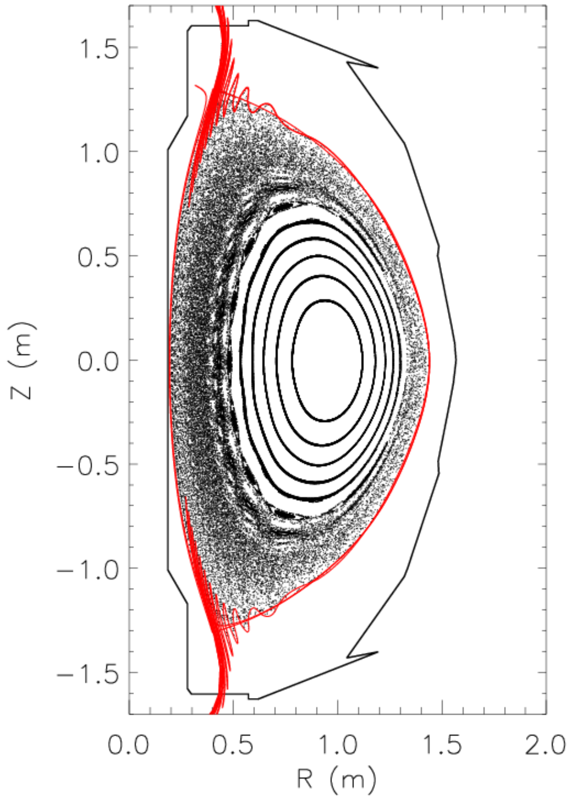
- Vacuum paradigm used in calculation
  - Superposition of n=3 field and axisymmetric field from 2D equilibrium reconstruction
- 150 field lines launched at each flux surface, distributed poloidally
- Distribution of radial coordinate of field lines (minor radius based on toroidal flux used here) gives field line diffusivity



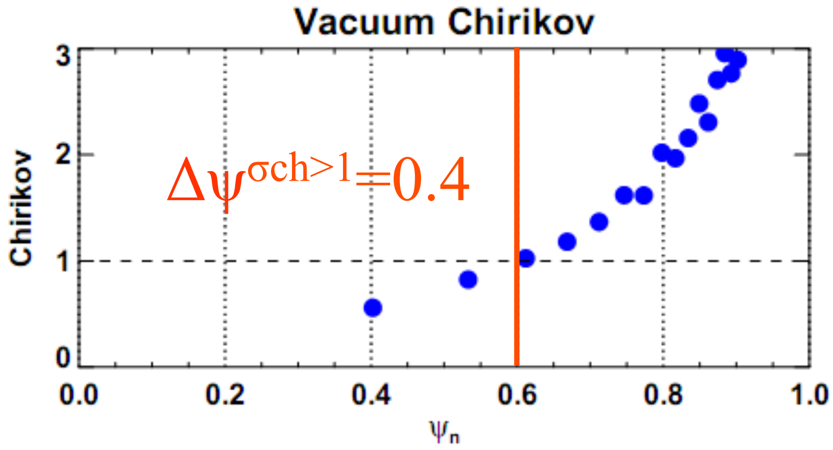


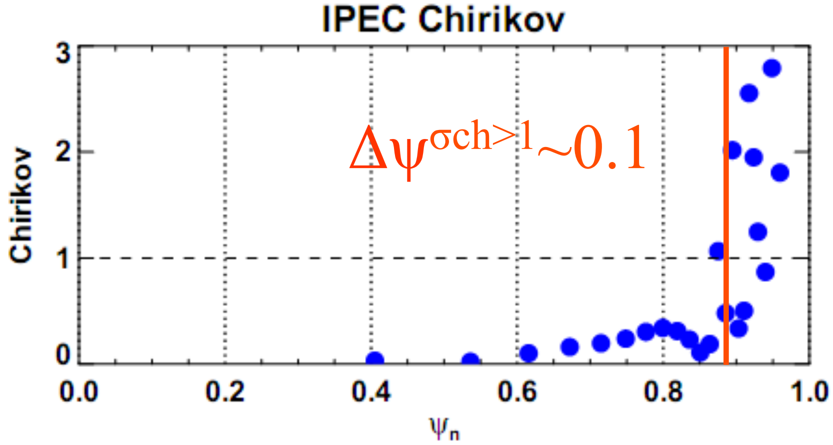
Resonant components are sufficient for edge stochasticity

- Vacuum and IPEC calculations give different regions of strong resonance
  - Vacuum case: $\sigma^{ch} > 1$ implies overlapping islands, stochasticity
  - IPEC: ideal plasma response -> σ^{ch} is a measure of resonant fields, no islands are allowed

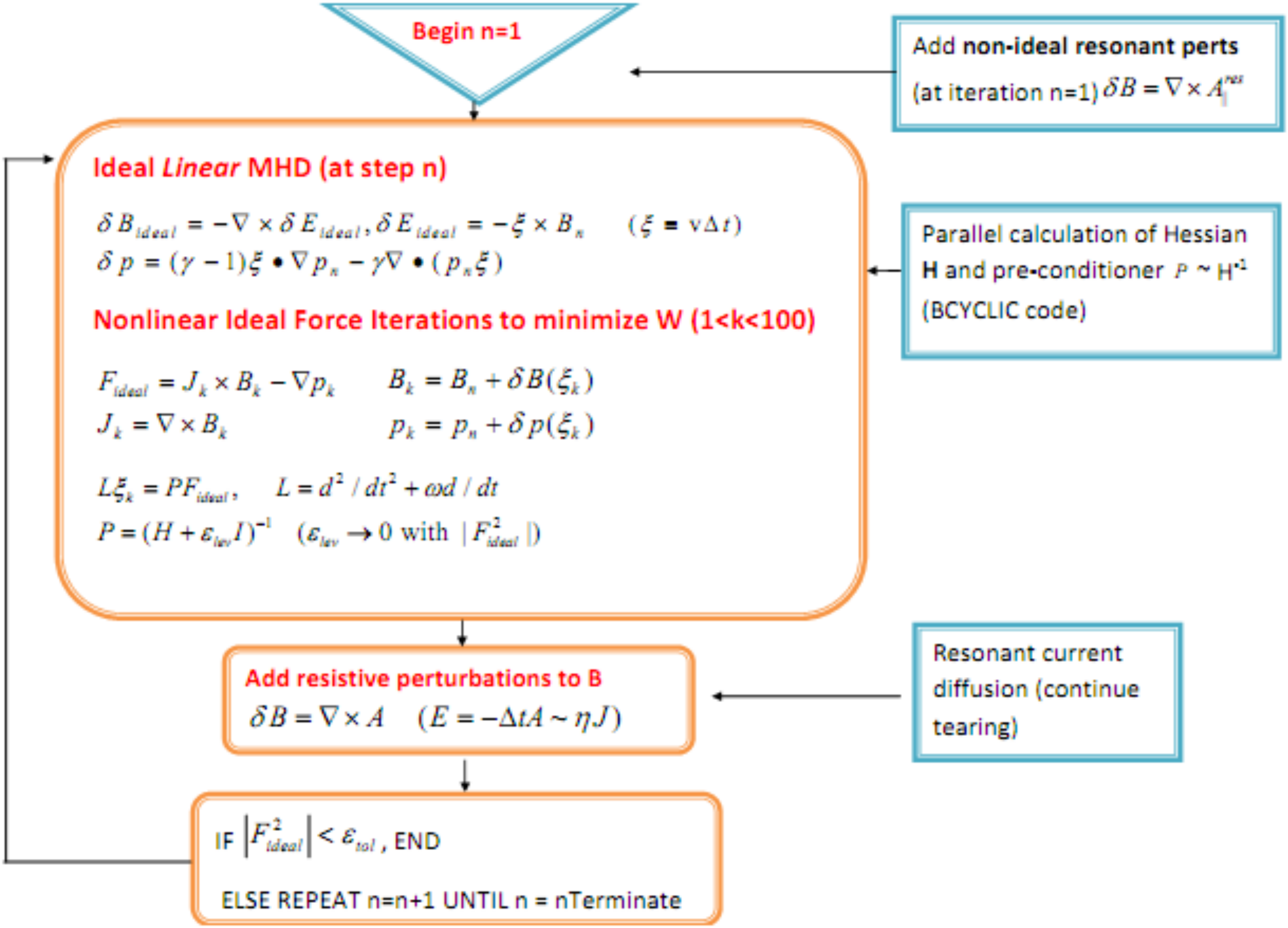


Vacuum fields





SIESTA iteration scheme



Begin n=1

Add **non-ideal resonant perts**

(at iteration n=1) $\delta B = \nabla \times A^{res}$

Ideal *Linear* MHD (at step n)

$$\delta B_{ideal} = -\nabla \times \delta E_{ideal}, \delta E_{ideal} = -\xi \times B_n \qquad (\xi = v \Delta t)$$

$$\delta p = (\gamma - 1)\xi \bullet \nabla p_n - \gamma \nabla \bullet (p_n \xi)$$

Nonlinear Ideal Force Iterations to minimize W (1<k<100)

$$F_{ideal} = J_k \times B_k - \nabla p_k \qquad B_k = B_n + \delta B(\xi_k)$$

$$J_k = \nabla \times B_k \qquad p_k = p_n + \delta p(\xi_k)$$

$$L\xi_k = PF_{ideal}, \qquad L = d^2/dt^2 + \omega d/dt$$

$$P = (H + \varepsilon_{lev} I)^{-1} \quad (\varepsilon_{lev} \to 0 \text{ with } |F^2_{ideal}|)$$

Parallel calculation of Hessian H and pre-conditioner $P \sim H^{-1}$ (BCYCLIC code)

Add resistive perturbations to B

$$\delta B = \nabla \times A \qquad (E = -\Delta t A \sim \eta J)$$

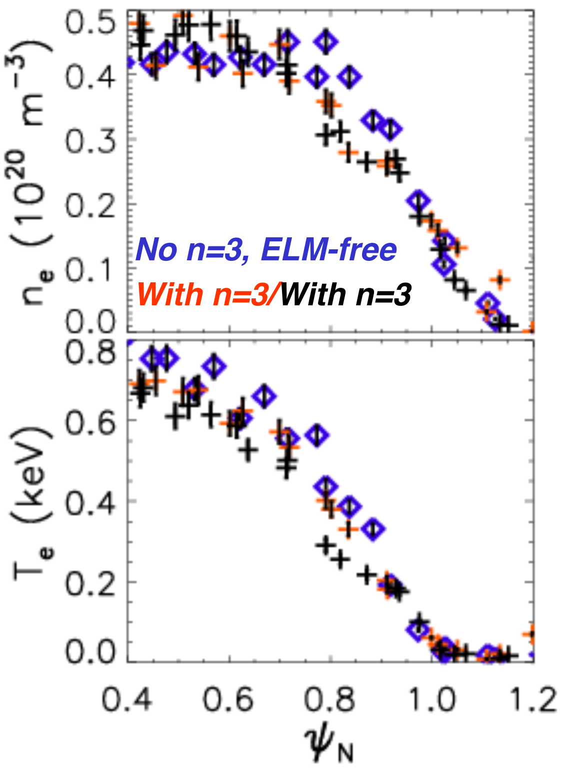
Resonant current diffusion (continue tearing)

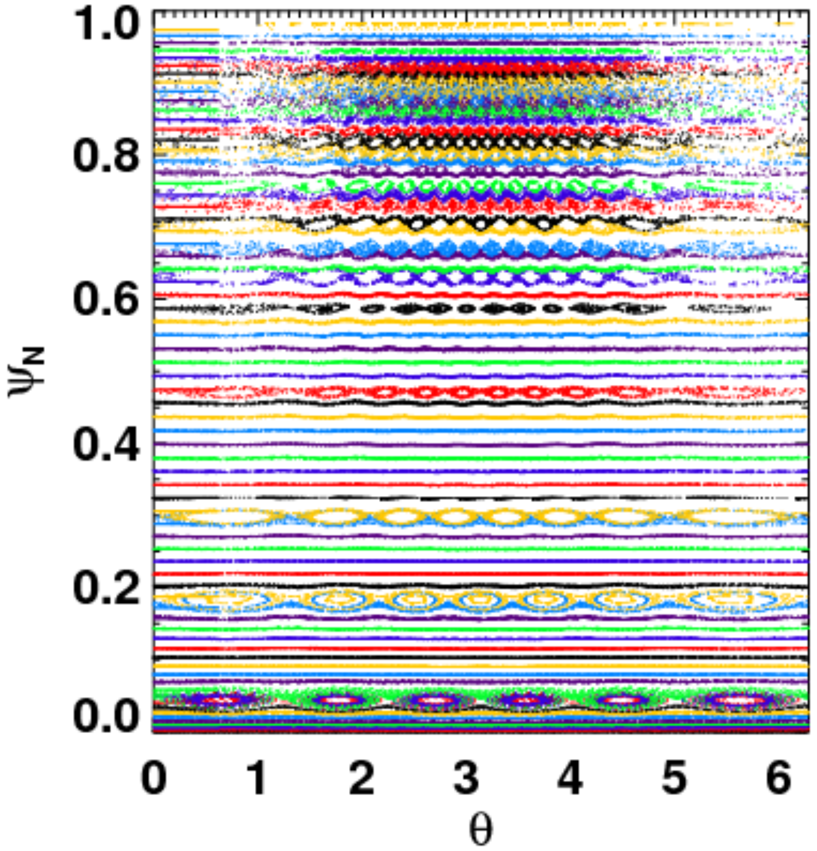
IF $\left|F^2_{ideal}\right| < \varepsilon_{tol}$, END

ELSE REPEAT n=n+1 UNTIL n = nTerminate

Second SIESTA case shows stronger island overlap near edge (ψ_N~0.83-0.9)

- Initial studies being done of NSTX discharge where T_e, n_e flattening seen during 3D field application
- Edge island overlap is observed in this case
  - Position is roughly consistent with flattering observed in experiment
  - More work needed to see if this may the cause of the flattening





Collisionality is high in ELM-triggering experiments

- Pedestal ν^* is typically ~1-3
- Case with Li conditioning, n=3 field just below ELM-triggering threshold
  - "Ears" in density profile flatten, but no gross pumpout